

Lepton flavor violation in the Simplest Little Higgs model

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Abstract

Little Higgs Models are a possible elegant solution to the hierarchy problem on the Higgs mass. As they predict naturally small deviations with respect to SM results, they are in agreement with all current experimental data. In this contribution, we review lepton flavor violation in the Simplest Little Higgs model focusing on semileptonic lepton flavor violating tau decays (where some new results are presented) and $H \rightarrow \ell\ell'$. Within this model, the most promising decay channels for discovering lepton flavor violation are $\mu \rightarrow e$ conversion in nuclei, $\mu \rightarrow e\gamma^{(*)}$, $\tau \rightarrow (e/\mu)\gamma$ and $\tau \rightarrow (e/\mu)(\pi^+\pi^-/\rho)$.

Keywords:

Lepton Flavor Violation, Tau decays, Higgs decays, Composite Higgs models

1. Motivation

I will start recalling the case for searches and studies of lepton flavor violation and also the interest of analysing it within (the Simplest) Little Higgs models.

1.1. Lepton Flavor Violation (LFV)

The discovery of neutrino oscillations evidences their non-vanishing mass and makes the charged lepton sector the only fermion subarea where flavor violation has not been unveiled yet. Moreover, the minimal extension of the SM with 3 massive neutrinos predicts non-zero (although undetectable) branching ratios for charged LFV processes, i. e. $B(\mu \rightarrow e\gamma) \sim 10^{-54}$ [1]. Therefore, the discovery of charged LFV would correspond, necessarily, to the effect of new dynamics.

For this reason there is an extensive hunt for new physics in searches for LFV muon, tau, Higgs, $Z^{(\prime)}$ decays and $\mu \rightarrow e$ conversion in nuclei; on which we had several experimental talks at this workshop [2] (see also the corresponding sections of [3]). Without dwelling in more detail into these, let us just highlight the impressive upper limit recently achieved by MEG $B(\mu \rightarrow e\gamma) \leq 4.2 \cdot 10^{-13}$ [4], which is a stringent constraint on

new physics models. In parallel to this exhaustive experimental activity there is not a corresponding effort on the theory side (but for the easiest $L \rightarrow \ell\gamma^{(*)}$ decays) and limited activity on the semileptonic LFV tau decays has been carried on [5].

LFV is not intrinsically related to any of the known problems of the Standard Model (SM): dark matter, baryon asymmetry of the universe, dark energy, (little) hierarchy problem, flavor problem, etc. However, it will be hopefully linked to any/some of them, so that its eventual measurement will shed light on any of these issues, helping to find the next standard theory.

1.2. Simplest Little Higgs (SLH) model

Little Higgs models arise as an elegant solution to the (little) hierarchy problem on the Higgs mass: since the Higgs boson couples proportionally to others' particles masses, its mass would get huge quantum loop corrections in the presence of generic heavy new physics. Therefore, $m_H \sim 125$ GeV would need to result from an extreme fine-tuning among the diverse corrections. A theoretically beautiful solution to this problem is provided by Supersymmetry, but the absence of SUSY particles at a TeV questions that Nature chose this way. An-

other classical solution to the problem comes from the analog with QCD. Technicolor and its different evolutions again face naturalness problems when confronted to the lack of their imprints on LHC data. Still, the idea of composite Higgs models [6] can be the starting point to formulate a theory in which the Higgs boson is naturally light that accords with all present observations.

Scalar boson masses are not protected by any symmetry, however the pion is so light because it is the pseudo-Nambu-Goldstone boson of chiral symmetry breakdown. The idea of LH models is to justify the small Higgs mass similarly, as a consequence of the breaking of a global symmetry. These models assume a scale of compositeness f (above which the new global symmetry is also displayed), which is much smaller than the electroweak vev ($f \geq 1$ TeV) and the structure of the model is arranged so that the Higgs mass is radiatively generated. There are new 'little' particles with masses of $O(f)$ and the UV completion of the model is expected at some tens of TeVs, where the theory would become strongly coupled ($4\pi f \gtrsim 12$ TeV). Thus we can expand perturbatively our amplitudes in v/f and keep only the leading term.

Among the LH models there are product group $([SU(2) \otimes U(1)]^N)$ and simple group models $(SU(N) \otimes U(1))$. Since the former need an ad-hoc symmetry (T-parity) to solve the hierarchy problem, we will take the simplest of the latter ($N = 3$) for our study of LFV tau [7] and Higgs decays [8] that we present in Sects. 3 and 4 preceded by a short account on the SLH model next (see also [9]).

2. A brief sketch of the SLH model

The symmetry structure of the SLH model [10] is given by $[SU(3) \otimes U(1)]_1 \otimes [SU(3) \otimes U(1)]_2$, where only the diagonal group is gauged. There are two different symmetry breakdowns (requiring two complex scalar fields, triplets under $SU(3)_1$ and $SU(3)_2$, respectively): on the one hand the gauged diagonal subgroup is broken down to the SM electroweak gauge group, yielding 5 Goldstone bosons which give mass to the additional 'little' gauge bosons (among these only W'^{\pm} and Z' play a rôle in our study). On the other hand, the global symmetry is broken similarly, with associated Goldstone bosons including the Higgs degrees of freedom.

Every fermion family contains a left-handed triplet (adding to the SM doublets one 'little' particle) and corresponding singlets. Heavy neutrinos, N_k ($k = 1, 2, 3$) are fundamental to our study, since they drive the LFV through their couplings. Though the quark sector is not

unambiguously defined, we will follow the anomaly-free embedding for the new quarks. Under reasonable assumptions, only the first generation 'little' quark, D , matters to our discussion [11].

3. LFV tau decays

We presented our results for $\tau \rightarrow \ell(P/PP/V)$ ($\ell = e, \mu$; P is short for pseudoscalar meson and V for vector resonance) in Ref. [7]¹. There we decided to include the effect of only two heavy neutrinos in our analysis. This corresponds to the case where there is a GIM-like mechanism acting in the mixing matrix among charged leptons and heavy neutrinos which effectively decouples N_3 . In this scenario, also the contributions of N_1 and N_2 cancel each other partially (according to the similarity of their masses). Here, instead, we will consider the most general scenario where no particular pattern of this mixing matrix is assumed. Generally, this will increase our predicted LFV observables.

The one-loop diagrams contributing to these decays can be seen in figures 1, 2 and 3 (with the γ -, $Z^{(\prime)}$ - and box-mediated contributions, respectively). We have computed them in the unitary gauge, where only physical particles appear. As a result, the cancellation of divergences becomes subtle, and the sum of the divergences of the penguin-like diagrams is cancelled by that of the box contributions. Parity forbids γ -mediated contributions to the processes with one pseudoscalar meson. However, since these and the box-mediated contributions turn out to be of similar magnitude² $\tau \rightarrow \ell P$ decays are predicted at a comparable rate to the $\tau \rightarrow \ell(PP/V)$ processes. Along our computation we have kept the leading term in the expansion parameter v/f and set m_ν , m_ℓ and M_τ to zero³.

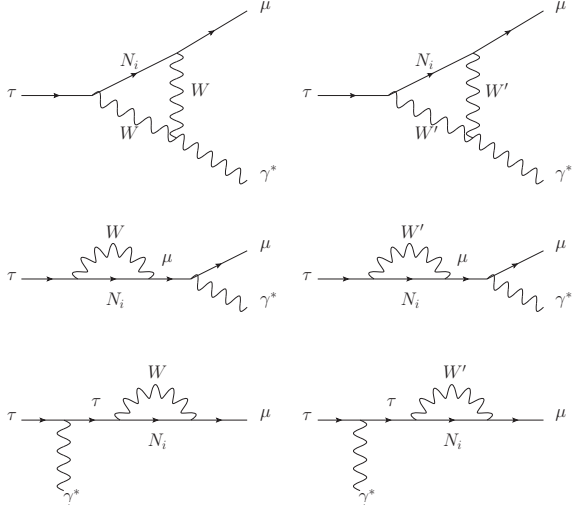
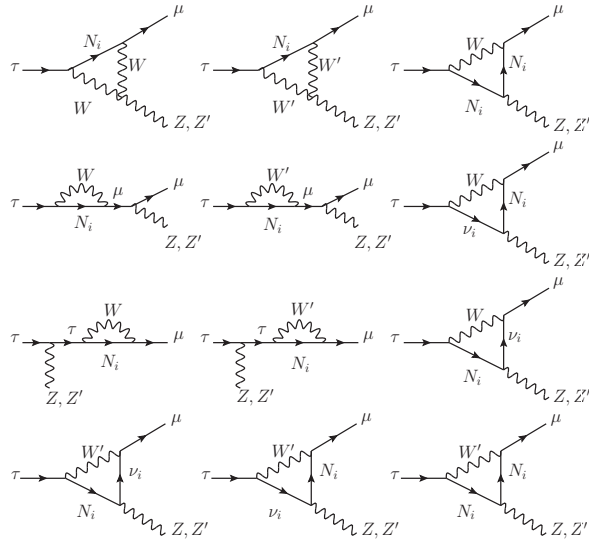
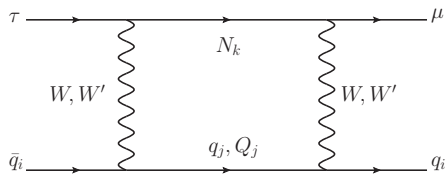
As a result of the embedding of the SM group into the SLH group, the only couplings entering the amplitudes are the SM $SU(2)$ and $U(1)$ couplings. In addition, the expressions depend on the ratios $\chi_j \equiv M_{N_j}^2/M_{W'}^2 \sim O(1)$ and $\omega \equiv M_W^2/M_{W'}^2 \ll 1$. $\delta_\nu = -v/(\sqrt{2}f \tan\beta)$ appears in the change between the flavor and mass bases for the (light and heavy) neutrinos and turns out to be an important parameter allowing to set the bound $f \tan\beta \leq 3.48$ TeV [11] (in the two-heavy neutrino scenario) studying $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$ and $\mu N \rightarrow eN$ in the SLH model⁴.

¹The SLH preserves lepton universality. As a result, we obtain the same branching ratios irrespective of $\ell = e, \mu$.

² Z and Z' contributions are negligible in all cases.

³ M_τ also sets the largest scale of external momenta, which are then negligible in the evaluation of the loop integrals.

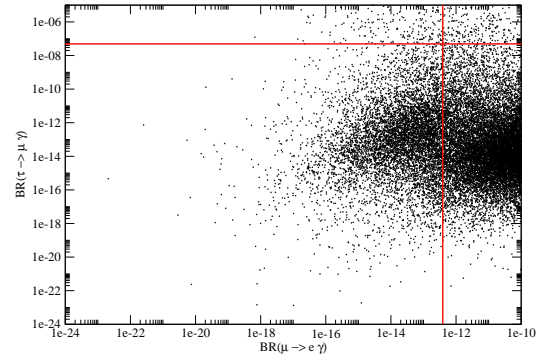
⁴A thorough discussion of the phenomenological relevance of these decays modes can be found in this reference.

Figure 1: Penguin-like diagrams for $\tau \rightarrow \mu \gamma^*$ in the SLH model.Figure 2: Penguin-like diagrams for $\tau \rightarrow \mu (Z/Z')$ in the SLH model.Figure 3: Box diagrams for $\tau \rightarrow \mu q \bar{q}$ in the SLH model. The internal quark states are $(u, \bar{u}) \rightarrow \{d, D\}$, $(d, \bar{d}) \rightarrow \{u\}$, $(s, \bar{s}) \rightarrow \{c\}$.

The remaining expressions contain quark bilinear currents which still need to be hadronized to make contact with the experimental searches. This is done in

an essentially model-independent way, writing those fermion bilinears in terms of the QCD quark currents and proceeding to their hadronization guided by chiral symmetry [12], axiomatic field theory properties implemented naturally through dispersion relations [13] and the QCD asymptotics [14], benefitting as well from the precise data at our disposal on two-meson factors. For these, we use the expressions given in Refs. [15]⁵.

For our phenomenological analysis within the SLH model, we have varied randomly the model parameters in the ranges $2 \text{ TeV} \leq f \leq 10 \text{ TeV}$, $1 \leq \tan \beta \leq 10$, keeping its product below 3.5 TeV. In the mixing matrix between charged leptons and heavy neutrinos we have neglected CP violation but kept it general otherwise. We have allowed for a factor of up to ten in the ratio between successive heavy neutrino masses and verified that all LFV low-energy constraints were satisfied before admitting a point in the model's parameter space. This restriction is needed, as can be seen from fig. 4.

Figure 4: $B(\mu \rightarrow e \gamma)$ vs. $B(\tau \rightarrow \mu \gamma)$ in the SLH model. The solid lines signal the upper limit at 90% C. L. for each mode.

Within the SLH model, the correlation between the most restricting low-energy process and the most abundant one- and two-meson LFV tau decays⁶ is plotted in figures 5 and 6, respectively. In both figures the x-axis is cut at the 90% C.L. upper limit for $B(\mu \rightarrow e \gamma)$. The

⁵In the one-meson case, the hadronization is encoded in the corresponding meson decay constant and the $\eta - \eta'$ mixing parameters [7]. The V cases can be obtained by considering the dominant PP channel with the di-meson system around the mass and width of the vector resonance ($\pi^+ \pi^-$ for the ρ and $K \bar{K}$ for the ϕ).

⁶ $B(\tau \rightarrow \mu \pi^+ \pi^-)$ and $B(\tau \rightarrow \mu \pi^0)$ are extremely correlated, as can be seen in [7]. This is a result of the hadronization process, as the $\pi^+ \pi^-$ channel is driven by the γ -exchange, while the one-pion mode is saturated by the box contribution.

solid line in Fig. 5 indicates the corresponding upper limit for $B(\tau \rightarrow \ell\pi^+\pi^-)$. A similar line is not shown on figure 6 because if the other low-energy restrictions on LFV processes are fulfilled, $B(\tau \rightarrow \ell\pi^0)$ is at least four orders of magnitude below its corresponding upper bound. Thus, in the SLH model, the only semileptonic LFV tau decays that can compete with $\mu N \rightarrow eN$, $\mu \rightarrow e\gamma$ and $\tau \rightarrow \ell\gamma$ as golden channels for the detection of LFV are $\tau \rightarrow \ell\pi^+\pi^-$ and $\tau \rightarrow \ell\rho$ (which is only a factor ~ 2 smaller than the $\pi^+\pi^-$ mode).

Three-dimensional plots that allow to represent the simultaneous dependence of the branching ratios on two model parameters can be found in my talk's file [16]. This, however, does not yield any new information (provided the GIM-like suppression is understood) with respect to the most conventional 2-D plots. Then, the dependence of the results on the model parameters is basically the one found for the case with only two effective heavy neutrinos in the 2-D plots of Ref. [7]: results depend quite mildly on f , $\tan\beta$, $\max\{|V^{i\mu}V^{i\tau}|\}$ ($\sin 2\theta$ for the GIM-like scenario) and the heavy neutrino spectroscopy. As expected, BRs:

- decrease with f according to the dependence of the amplitude on $(v/f)^2$,
 - are almost constant for $\tan\beta \geq 3$, while they exhibit a marked narrow dip around $\tan\beta = 2$, where the BR is reduced by an order of magnitude.
 - increase as $\sin^2 2\theta$ (similarly for $\max\{|V^{i\mu}V^{i\tau}|\}$).
 - vary smoothly with the neutrino masses hierarchy.
- In the GIM-like case, the suppression of the BRs gets stronger for $M_{N_1} \sim M_{N_2}$.

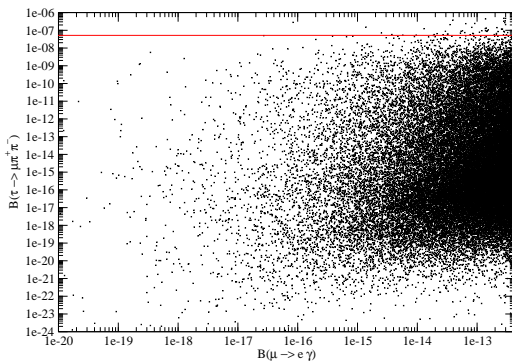


Figure 5: Correlation between $B(\mu \rightarrow e\gamma)$ and $B(\tau \rightarrow \mu\pi^+\pi^-)$ in the SLH model.

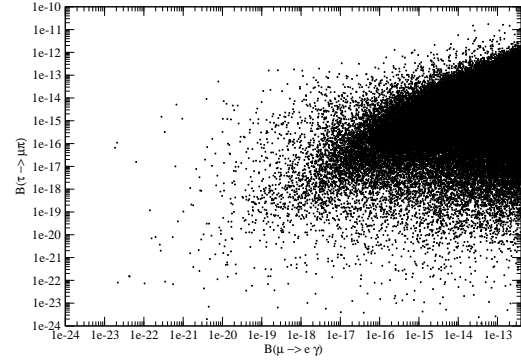


Figure 6: Correlation between $B(\mu \rightarrow e\gamma)$ and $B(\tau \rightarrow \mu\pi^0)$ in the SLH model.

4. LFV Higgs decays

It has not been necessary to update our analyses of $H \rightarrow \ell\ell'$ [8]. The dependence on the model parameters follows the patterns explained in Sect. 3. As it can be seen in fig. 7, even in the case with three active heavy neutrinos (where the considered LFV Higgs decays BRs are four orders of magnitude larger than in the GIM-like scenario [8]) the SLH predicts unmeasurable BRs at LHC, provided the low-energy constraints on LFV processes are satisfied. Similar small BRs for these decays have been found recently within LH models [17]⁷. We refer the reader to Ref. [8] for a complete discussion of our results on LFV Higgs decays.

5. Conclusions

Little Higgs models (particularly SLH) remain as elegant candidates to alleviate the hierarchy problem on the Higgs mass, respecting all experimental bounds. (S)LH models predict small LFV decay rates which could escape detection at Belle-II and (specially) at LHC. Within SLH, LFV detection should be easier for a general (not GIM-like) pattern of the 3 heavy neutrinos of the model. In that case, the most promising channels for its discovery would be $\mu N \rightarrow eN$, $\mu \rightarrow e\gamma$, $\tau \rightarrow (e/\mu)\gamma$ and $\tau \rightarrow (e/\mu)(\pi^+\pi^-/\rho)$.

⁷SLH models also predict generally small departures from the SM in Higgs couplings, which are in good agreement with present measurements [18].

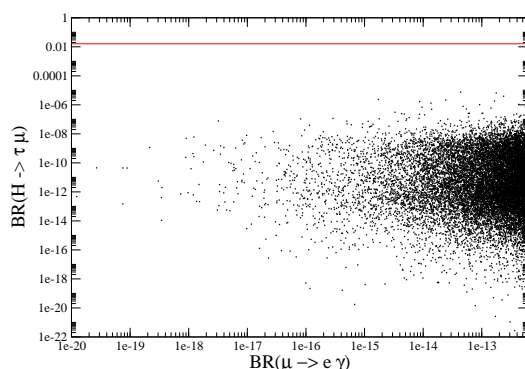


Figure 7: Correlation between $B(\mu \rightarrow e\gamma)$ and $B(H \rightarrow \tau\mu)$ in the SLH model. The solid line shows the 95% C.L. upper limit set by the LHC experiments.

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